



# Flame Tube NO<sub>x</sub> Emissions Using a Lean-Direct-Wall-Injection Combustor Concept

Robert R. Tacina  
Glenn Research Center, Cleveland, Ohio

Changlie Wey  
QSS Group, Inc., Brook Park, Ohio

Kyung J. Choi  
Drexel University, Philadelphia, Pennsylvania

## The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA Access Help Desk at 301-621-0134
- Telephone the NASA Access Help Desk at 301-621-0390
- Write to:  
NASA Access Help Desk  
NASA Center for Aerospace Information  
7121 Standard Drive  
Hanover, MD 21076



# Flame Tube NO<sub>x</sub> Emissions Using a Lean-Direct-Wall-Injection Combustor Concept

Robert R. Tacina  
Glenn Research Center, Cleveland, Ohio

Changlie Wey  
QSS Group, Inc., Brook Park, Ohio

Kyung J. Choi  
Drexel University, Philadelphia, Pennsylvania

Prepared for the  
37th Joint Propulsion Conference and Exhibit  
cosponsored by the AIAA, ASME, SAE, and ASEE  
Salt Lake City, Utah, July 8–11, 2001

National Aeronautics and  
Space Administration

Glenn Research Center

Available from

NASA Center for Aerospace Information  
7121 Standard Drive  
Hanover, MD 21076

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22100

Available electronically at <http://gltrs.grc.nasa.gov/GLTRS>

# FLAME TUBE NO<sub>x</sub> EMISSIONS USING A LEAN-DIRECT-WALL-INJECTION COMBUSTOR CONCEPT

Robert R. Tacina\*

National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

Changlie Wey

QSS Group, Inc.  
Brook Park, Ohio 44142

Kyung J. Choi\*

Drexel University  
Philadelphia, Pennsylvania 19104

## ABSTRACT

A low-NO<sub>x</sub> emissions combustor concept has been demonstrated in flame tube tests. A lean-direct injection concept was used where the fuel is injected directly into the flame zone and the overall fuel-air mixture is lean. In this concept the air is swirled upstream of a venturi section and the fuel is injected radially inward into the air stream from the throat section using a plain-orifice injector. Configurations have two-, four-, or six-wall fuel injectors and in some cases fuel is also injected from an axially located simplex pressure atomizer. Various orifice sizes of the plain-orifice injector were evaluated for the effect on NO<sub>x</sub>. Test conditions were inlet temperatures up to 810K, inlet pressures up to 2760 kPa, and flame temperatures up to 2100K. A correlation is developed relating the NO<sub>x</sub> emissions to inlet temperature, inlet pressure, fuel-air ratio and pressure drop. Assuming that 15 percent of the combustion air would be used for liner cooling and using an advanced engine cycle, for the best configuration, the NO<sub>x</sub> emissions using the correlation is estimated to be <75 percent of the 1996 ICAO standard.

## INTRODUCTION

Engines in most commercial aircraft today meet the current 1996 International Civil Aviation Organization, (ICAO) landing-takeoff NO<sub>x</sub> characteristic level, LTO NO<sub>x</sub>, limits with some margin. Concerns, however, are increasing about the effect of cruise NO<sub>x</sub> emissions on the ozone layer and global warming. Landing fees based on NO<sub>x</sub> emissions are being assessed by Sweden and Switzerland and could become more common and possibly

even limit the access to some countries or airports. Although an increase in overall engine efficiency from a higher engine pressure ratio decreases the amount of the greenhouse gases CO<sub>2</sub> and H<sub>2</sub>O, it also increases the amount of NO<sub>x</sub>. To ensure that the next generation of aircraft are as clean as possible, one of the NASA goals is to reduce NO<sub>x</sub> emissions of future aircraft by a factor of three within 10 years and a factor of five within 20 years. The purpose of this paper is to describe a method to reduce NO<sub>x</sub> emissions that could be applicable to a wide range of engines and pressure ratios.

NO<sub>x</sub> formation on the lean-side of stoichiometry is essentially an exponential function of flame temperature. The key to NO<sub>x</sub> reduction is to therefore, burn the fuel at the lowest possible flame temperature. This is not only equivalent to burning as lean as possible but also with as uniform a mixture as possible to avoid locally stoichiometric zones that produce high amounts of NO<sub>x</sub>. Lean, premixed, prevaporized (LPP) combustion satisfies these criteria and is commonly used in ground-power applications with great success in reducing NO<sub>x</sub> emissions. For an aircraft application, however, there are concerns with auto-ignition and flashback in the premixing zones because of higher pressures and temperatures associated with aircraft engines. Also, LPP systems are susceptible to acoustic instabilities (which is a major problem in ground-power applications as well).

An alternative to LPP schemes is lean-direct injection (LDI) combustion. An LDI system differs from an LPP system in that the fuel is injected directly into the flame zone and, thus, does not have a potential for auto-ignition or flashback. As the fuel is not premixed and prevaporized, it is, however, important to achieve fine atomization and mixing of the fuel and air, quickly and uniformly, so that

---

\*AIAA member

flame temperatures are low and NO<sub>x</sub>-formation levels near those of LPP systems. The potential for low-NO<sub>x</sub> LDI combustors has been demonstrated by Anderson,<sup>1</sup> Alkabie and Andrews,<sup>2</sup> Schaefer and Samuelsen,<sup>3</sup> and Terasaki and Hayashi<sup>4</sup>. Tacina<sup>5</sup> has shown that NO<sub>x</sub> emissions from an LDI combustor can approach those of LPP combustors.

In the LDI concept described in this report, fuel is injected into a swirling airflow from a fuel injector located on the combustor wall or mixer wall. This concept is called lean-direct-wall-injection, LDWI. Important aspects of this technique are: (1) a liquid jet should be utilized (not a thin-film, hollow-cone spray typical of a conventional pressure-swirl atomizer), and (2) the jet should be injected radially inward from the mixer wall toward the approaching swirling airflow at an inclined angle with respect to the radial direction, Choi.<sup>6</sup> The advantage of the LDWI concept is its use of a swirling airflow both for atomizing the injected liquid jet(s) and for mixing the atomized spray(s) in a short period of time. In the case of coaxially injected sprays, the strong centripetal forces of swirling airflow tend to sustain the liquid droplets (or fuel vapor) inside the core recirculating zones, resulting in a relatively slow mixing process. In the LDWI mode, however, the swirling airflow abruptly breaks the liquid jet into small droplets and the droplets are mixed quickly, within 25 mm downstream of the injection point.

Another advantage of this concept is that an LDWI combustor uses a simple, plain-orifice, fuel injector, i.e., an orifice at the end of a fuel tube. Using simple fuel injectors has the potential of reducing maintenance problems such as clogging and coking, especially for advanced gas-turbine engines that operate at high inlet air temperatures and pressures.

In this paper, emission measurements are reported for a single module, in a 76.2-mm diameter flame-tube with uncooled ceramic-cast walls. The test conditions are inlet pressures up to 2760 kPa, inlet temperatures up to 820K and flame temperatures up to 2100K. A correlation is developed relating the NO<sub>x</sub> emissions to inlet pressure, inlet temperature, fuel-air ratio and pressure drop.

## CONFIGURATIONS

The basic configuration of the LDWI module tested is shown in Fig. 1 and is a design by Choi and Tacina.<sup>7</sup> The air swirler has 12 blades with a 45° blade angle. The outer diameter of the air swirler is 66 mm and the inner diameter is 36.6 mm. The Venturi section has a 44-mm diameter throat and a 45° wall-angle upstream and downstream of the throat. The fuel injectors are located 8 mm upstream of the throat.

Table 1 lists the seven variations to the basic configuration that were tested. The flow number, defined as fuel flow rate in kg/s divided by the square root of the product of fuel differential-pressure in Pa and fuel density in kg/m<sup>3</sup>, was measured for each configuration and is given in dimensions of mm<sup>2</sup>. The discharge coefficient is the flow number multiplied by the square root of two (which equals the effective area) divided by physical area. Configuration D, Fan-Spray, had a fuel injector that consisted of an elliptical slot. Of the four Fan-Spray injectors two have slot dimensions of 0.381×1.778 mm and two are 0.381×1.524 mm, with the short dimension in the circumferential direction and long dimension in the radial direction.

In Fig. 2 the Flow Number for the individual fuel injectors is plotted as a function of fuel orifice diameter.

## EXPERIMENTAL FACILITY

A schematic of the experimental facility is shown in Fig. 3. The incoming combustion air is heated by a non-vitiated heat exchanger to a maximum temperature of 840K and a maximum pressure of 3000 kPa. The flow is measured by a venturi meter, and fuel-flow rate is measured by a turbine meter. The fuel-injector module is mounted in a stainless-steel pipe with a 152-mm inside diameter. The fuel-air mixture is injected into a flame tube that has a diameter of 76.2 mm. The flame tube flow passage is made of zirconium (ZrO), 12 mm thick, that is housed in a 152-mm diameter pipe. The gap between the zirconium tube and the pipe is filled with an alumina (Al<sub>2</sub>O<sub>3</sub>) casting. The outside of the pipe is cooled by a water coil. The test section is 300-mm long, followed by a water-quench section and back-pressure valve. Gas sampling is done 203 mm from the fuel-injector exit except for configurations D and G for which the data were taken at 305 mm downstream. A three-hole, water-cooled probe was used with the holes equally spaced across the diameter of the flame tube. There is a single-hole traversing probes located at 102 mm from the fuel-injector exit for radial-profile measurements. The concentrations of O<sub>2</sub>, CO, CO<sub>2</sub>, HC (as CH<sub>4</sub>), NO, and NO<sub>x</sub> are measured by standard, gas-analysis procedures, SAE:<sup>8</sup> chemiluminescence for NO, nondispersive infrared absorption for CO and CO<sub>2</sub>, flame ionization for HC, and paramagnetic analysis for O<sub>2</sub>. The NO<sub>2</sub>-NO converter is calibrated using standard NO<sub>2</sub> to verify that conversion efficiencies are >96 percent. The overall accuracy of the emission measurements are estimated to be within 90 percent. This is based on the repeatability of data when the same configuration was tested on different days and with at least one change of configurations between tests of the same configuration.

## RESULTS AND DISCUSSION

The NO<sub>x</sub> emissions are plotted versus the adiabatic flame temperature for each configuration in Fig. 4 at various test conditions. The NO<sub>x</sub> values are given in terms of the emission index, g NO<sub>2</sub>/kg fuel, where the emissions of NO are calculated as NO<sub>2</sub>. Although the plots in the individual figures are shown at nominally the same inlet conditions, the EI's are corrected for small differences by the following:

$$\text{EINOx}_{\text{plot}} = (\text{EINOx}_{\text{actual}}) \left( \frac{P_{3,\text{plot}}}{P_{3,\text{actual}}} \right)^{0.595} \left\{ \exp(T_{3,\text{plot}} - T_{3,\text{actual}}) \right\} \left( \frac{\Delta P_{\text{plot}}}{\Delta P_{\text{actual}}} \right)^{-0.566} \quad (1)$$

where “plot” refers to the condition labeled in the plot and “actual” refers to the test condition. These correction factors are based on a correlation developed at NASA based on many configurations tested in the Advanced Subsonic Technology (AST) Program, both from industry and NASA configurations. All the NO<sub>x</sub> data are plotted at conditions where the combustion efficiency is >99.9 percent. The adiabatic flame temperature is determined from the inlet conditions and the gas-sample fuel-to-air ratio. The NO<sub>x</sub> emissions for these plots are from the probe located 203 mm downstream of the fuel-injector face. The fuel-air ratio as determined by the emissions measurement is compared to the metered fuel-air ratio and generally are within 5 percent of each other.

A number of effects can be observed from Fig. 4. First, the plot of the log of NO<sub>x</sub> Emission Index (EINO<sub>x</sub>) as a function of flame temperature is nearly linear for configurations D to G but curves upwards for configurations A to C. Also the EINO<sub>x</sub> has a greater dependence on flame temperature for configurations A to C. Finally, EINO<sub>x</sub> increases with increasing inlet temperature and pressure and decreases with increasing pressure drop (which is accomplished through increased airflow). These effects will be discussed in more detail in the paragraph on the data correlations.

Configurations D to F were tested with 2 fuel injectors flowing instead of all 4 (810K, 2070 kPa, 4 percent ΔP). As can be seen in Fig. 4 the NO<sub>x</sub> was significantly higher (approximately a factor of two at a flame temperature of 1800K).

In configurations A to C a center pressure-swirl atomizing fuel-injector was used with a flow number of

0.187, where 20 percent of the fuel went to the center injector and 80 percent to the wall injectors. As can be seen in Fig. 4(a) to (c), the NO<sub>x</sub> emissions were significantly higher when the center injector was used. This indicates that the fuel-air mixing is not as uniform with the use of a center fuel-injector.

The EINO<sub>x</sub> for the various configurations are compared in Fig. 5 (for all fuel injectors flowing, i.e., 6 injectors flowing in configuration A and 4 injectors flowing in configurations B to G). The NO<sub>x</sub> emissions from configurations D to G are similar. Configurations A, to C have lower NO<sub>x</sub> emissions at lower flame temperatures but they have a greater dependence on flame temperature. At high flame temperatures (>1900 K), configurations B and C have higher NO<sub>x</sub> emissions than D to G. The NO<sub>x</sub> emissions from configuration A are lower than that of any other configuration at all conditions tested, although if the data is extrapolated to flame temperatures above 2100K the NO<sub>x</sub> emissions would probably be higher than Configurations D to G.

The effect of flow number on the NO<sub>x</sub> emissions is plotted in Fig. 6. The larger the flow number the smaller the pressure drop across the fuel injector and thus is a measure of the penetration of the fuel into the air stream. The NO<sub>x</sub> emissions are relatively insensitive to flow number above values of 0.241. Below a flow number of 0.241 the NO<sub>x</sub> decreases with decreasing flow number except at the condition of T<sub>3</sub> = 810 K, P<sub>3</sub> = 2760 kPa, T<sub>f</sub> = 2000K where the NO<sub>x</sub> was higher at a flow number of 0.201 than at a flow number of 0.241. This indicates that greater penetration is achieved with a smaller flow-number injector and is beneficial. However it is not a simple matter of penetration because, as noted above when configurations D to F were tested with 2 fuel injectors flowing instead of all 4, the NO<sub>x</sub> was substantially higher (approximately a factor of two at a flame temperature of 1800K) even though with only two fuel injectors flowing the penetration should be significantly greater.

Another factor that could affect mixing and NO<sub>x</sub> production is that, with smaller flow-number (smaller orifice) injectors, the drop sizes should be smaller for the same fuel flow. Smaller drops would follow the airflow more closely and evaporate more quickly, thus improving the fuel and air mixing.

In Fig. 7, NO<sub>x</sub> data is plotted using the correlation developed at NASA based on many configurations tested in the Advanced Subsonic Technology (AST) Program, both from industry and NASA configurations. The correlation uses the measured inlet conditions of temperature, pressure and fuel-air ratio, and the measured pressure drop to correlate the EINO<sub>x</sub>.

$$\text{EINO}_x = C P_3^{0.595} \exp\left(\frac{T_3}{194}\right) \text{FAR}^{1.688} \left(\frac{\Delta P}{P}, \%\right)^{-0.565} \quad (2)$$

where C is a constant determined from the regression analysis,  $P_3$  is the inlet pressure in kPa,  $T_3$  the inlet temperature in K, FAR is the fuel-air ratio and  $\Delta P/P$  is the pressure drop across the fuel injector in percent.

The correlation is plotted using the open-square symbols in Fig. 7. The correlation is a good fit for configurations D to G although there is some scatter with configuration F. However, configurations A to C have a different dependence on flame temperature, as shown in Fig. 4, and thus require a different correlation.

The second correlation, solid-circle symbols, is a fit based on the data from configurations A to C. (There was no improvement in a specific fit for configurations D to G compared to the AST correlation.) For configurations A and C it was found that the effect of inlet pressure, inlet temperature and pressure drop is the same as in the AST correlation and the only change necessary was in the fuel-air ratio term.

$$\text{EINO}_x = 17580 P_3^{0.595} \exp\left(\frac{T_3}{194}\right) \text{FAR}^{4.63} \left(\frac{\Delta P}{P}, \%\right)^{-0.565} \quad (3)$$

$$\text{EINO}_x = 2750 P_3^{0.595} \exp\left(\frac{T_3}{194}\right) \text{FAR}^{1.688} \left(\frac{\Delta P}{P}, \%\right)^{-0.565} \quad (4)$$

For configuration B it was also necessary to modify the terms involving inlet temperature and pressure drop to reflect an increased effect of inlet temperature and slightly decreased dependence of pressure drop.

$$\text{EINO}_x = 9774 P_3^{0.600} \exp\left(\frac{T_3}{98}\right) \text{FAR}^{5.57} \left(\frac{\Delta P}{P}, \%\right)^{-0.500} \quad (5)$$

It is interesting to note that with configurations A to C, when the terms in the AST correlation for the effect of inlet temperature, pressure and pressure drop are used, the exponent for the fuel-air ratio term varies inversely with the flow number or fuel-injector orifice size. A greater dependence on flame temperature or fuel-air ratio suggests that configurations A to C are closer to a premixed flame than the AST configurations, and configurations D to G.

Also the dependence on flame temperature for configuration A to C is greater than that of premixed flames. A possible explanation is that at high flame temperatures burning occurs earlier in the mixing process.

Using the correlation from configuration A, the ICAO landing-takeoff NO<sub>x</sub> characteristic level, LTO NO<sub>x</sub>, International Standards and Recommended Practices,<sup>9</sup> (parameter that integrates emissions over a landing/takeoff-cycle) is calculated and compared to the ICAO standards for 55:1 and 30:1 pressure-ratio engines using a hypothetical advanced engine cycle from the NASA Ultra Efficient Engine Technology program, see Tables 2 and 3, and typical low power NO<sub>x</sub> values. Here 15 percent of the air was assumed to be used for cooling for the large engines and 20 percent cooling for the regional engines. The LTO NO<sub>x</sub> numbers are 77 percent below the standards for large engines and 75 percent below the standard for regional size engines. Note that these are based on data from flame-tube experiments and may not be indicative of a real engine.

The combustion efficiency for all the configurations and various conditions are shown in Fig. 8. For all configurations and for the range of conditions with inlet temperatures between 700 and 810K, and inlet pressures between 1380 and 2760 kPa, the combustion efficiency is >99.9 percent for flame temperatures above 1600K. Since the purpose of this research is to determine the low NO<sub>x</sub> potential for LDWI, data was not taken at lower flame temperatures to determine the limits for high-efficiency operation. It is assumed that for low power operation, a center fuel injector would be used and separate development of the optimum center injector would be required.

For configurations A to C, radial profiles of fuel-air ratio, NO<sub>x</sub>, CO and combustion efficiency are shown in Fig. 9. The vertical profiles were taken at an axial location of 102 mm downstream of the module. For configuration B, only one-half of the profile was taken because of problems with the traversing mechanism. For configurations A and C, the fuel distribution (as shown by fuel-air ratio) is nearly uniform although it is not symmetrical, with the fuel-air ratio being lower near one wall. The variation is about +10 percent with the variation increasing to about -20 percent near one wall. The NO<sub>x</sub> and CO emissions varied in exactly the same way as the fuel distribution, i.e., where the fuel concentration is high the NO<sub>x</sub> and CO are high. The combustion efficiency varies inversely with CO and is essentially the mirror image of the CO plot.

From the profiles, the fuel distribution (as given by fuel-air ratio) is slightly more uniform for configuration C compared to that of A, i.e., a lower-root-mean-square of the differences from the mean. This should result in a lower EINO<sub>x</sub> for configuration C, however, the EINO<sub>x</sub> is significantly lower for configuration A. A possible



explanation is that the rate of mixing was faster for configuration A and that at the time of burning the fuel was more uniformly distributed for configuration A. Also, only one profile was taken and different distributions may have been found if other radial profiles were taken.

## SUMMARY AND CONCLUSIONS

A low-NO<sub>x</sub>, lean-direct-wall-injection concept has been demonstrated in flame-tube tests. The fuel is injected directly into the flame zone and the overall fuel-air mixture is lean. In this concept, the air is swirled upstream of a venturi section and the fuel is injected radially inward into the air stream upstream of the throat using a plain-orifice fuel-injector. The configurations had two-, four-, or six-wall fuel-injectors and in some cases fuel was also injected from a simplex pressure atomizer located at the center of the air swirler. Various orifice sizes of the plain-orifice fuel-injector were evaluated for the effect on NO<sub>x</sub> production. Test conditions ranged from inlet temperatures up to 810K, inlet pressures up to 2760 kPa, and flame temperatures up to 2100K. The NO<sub>x</sub> levels were quite low for the best configuration. With the 6 fuel-injector array, at an inlet temperature of 810K, inlet pressure of 2760 kPa, pressure drop of 4 percent and a flame temperature of 1900K, the NO<sub>x</sub> emission index was <9. The NO<sub>x</sub> emission levels were lower with the 6-fuel-injector configuration than with the 4-injector configuration which were in turn lower than with the 2 injector configuration. With the 4-injector array flow number or orifice size was varied. Over the range tested, the NO<sub>x</sub> emissions increased as flow number increased from 0.169 to 0.241 mm<sup>2</sup> and then remained relatively constant with an increase to 0.776 mm<sup>2</sup>. A correlation was developed relating the NO<sub>x</sub> emission index to inlet temperature, inlet pressure, fuel-air ratio and pressure drop. For the lowest NO<sub>x</sub> configuration, the correlation had the usual dependence on inlet pressure, inlet temperature and pressure drop, but the effect of fuel-air ratio was greater than is usually reported and more similar to that of a premixed combustor. For a 55:1 pressure-ratio engine, and assuming that 15 percent of the combustion air would be used for liner cooling in an advanced engine cycle, the NO<sub>x</sub> emission index from the configuration-A correlation

was estimated to be <77 percent of the 1996 ICAO standard. For a 30:1 pressure ratio engine and assuming 20 percent cooling flow, it would be a 75 percent reduction from the ICAO standard.

## REFERENCES

1. Anderson, D.N., (1981). Ultra Lean Combustion at High Inlet Temperatures, ASME Paper 81-GT-44, *Gas Turbine Conference & Products Show*, Houston TX, 1981.
2. Alkabie, H.S., Andrews, G.E., and Ahmad, N.T, (1988). Lean Low NO<sub>x</sub> Primary Zones Using Radial Swirlers, paper ASME 88-GT-245, *ASME Gas Turbine and Aero Engine Congress and Exposition*, Amsterdam, 1988.
3. Schaefer, S.W., and Samuelsen, G. S., (1998). A Liquid Fueled, Lean Burn, Gas Turbine Combustor Injector, *Combustion Science and Technology*, Vol. 139, pp. 41-47.
4. Terasaki, T., and Hayashi, S. (1995). Lean Non-Premixed Combustion for Low-NO<sub>x</sub> Gas Turbine Combustor, *Yokohama International Gas Turbine Congress*, Yokohoma, 1995.
5. Tacina, R.R., (1990). Low NO<sub>x</sub> Potential of Gas Turbine Engines, AIAA Paper 90-0550, *28<sup>th</sup> Aerospace Science Meeting*, Reno NV, 1990.
6. Choi, K., Huh, J., and Tacina, R., (1998). Studies on Well-Stirred Mixing of Liquid Droplets in a Lean Direct Injection Mode, *11<sup>th</sup> Annual Conference on Liquid Atomization and Spray Systems*, ILASS-America 98, Cleveland, Ohio, Sacramento, CA, pp. 273-277.
7. Choi, K. and Tacina, R., "Lean Direct Wall Fuel Injection Method and Devices," U.S. Patent (6,067,790), May 2000.
8. SAE ARP1533—"Procedure for the Calculation of Gaseous Emissions from Aircraft Turbine Engines," 1996.
9. International Standards and Recommended Practices, Environmental Protection, Annex 16 to the Convention on International Civil Aviation, Vol. II, Aircraft Engine Emissions, Second Edition-July 1993.

TABLE 1.—CONFIGURATIONS

Configuration	Number of wall fuel injectors	Wall-fuel injector orifice size, mm	Wall-injector flow number, mm <sup>2</sup>	Discharge coefficient	Center injector flow number, mm <sup>2</sup>
A	6	0.457	0.169	0.729	0.187
B	4	0.533	0.201	0.636	0.187
C	4	0.610	0.241	0.583	0.187
D	4 or 2	1.778 or 1.524×0.381	0.468	0.744	-----
E	4 or 2	0.838	0.482	0.617	-----
F	4 or 2	1.016	0.669	0.583	-----
G	4	1.181	0.776	0.501	-----

TABLE 2.—LARGE ENGINE CYCLE

	Power, percent	Time, min	Pt3.0, kPa	T3.0, K	ΔP/P	FARt
SLTO	100.0	0.7	5426	970	0.04	0.0289
Climb	85.0	2.2	4709	934	0.04	0.0266
Approach	30.0	4	2055	740	0.04	0.0157
Idle	7.0	26	993	615	0.04	0.0093

TABLE 3.—REGIONAL ENGINE CYCLE

	Power, percent	Time, min	Pt3.0, kPa	T3.0, K	ΔP/P	FARt
SLTO	100.0	0.7	3041	828	0.04	0.03190
Climb	85.0	2.2	2655	792	0.04	0.02896
Approach	30.0	4	1158	637	0.04	0.01998
Idle	7.0	26	414	505	0.04	0.01515

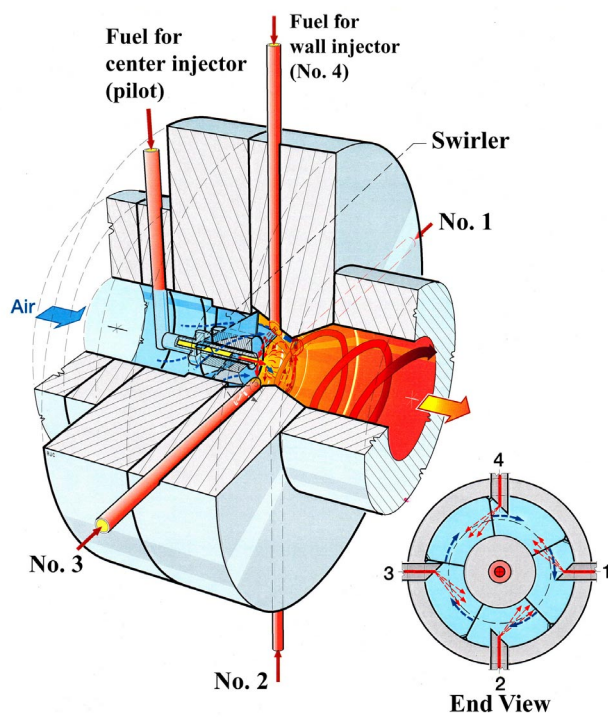


Figure 1. - Ultra low NO<sub>x</sub> combustion - lean direct wall injector

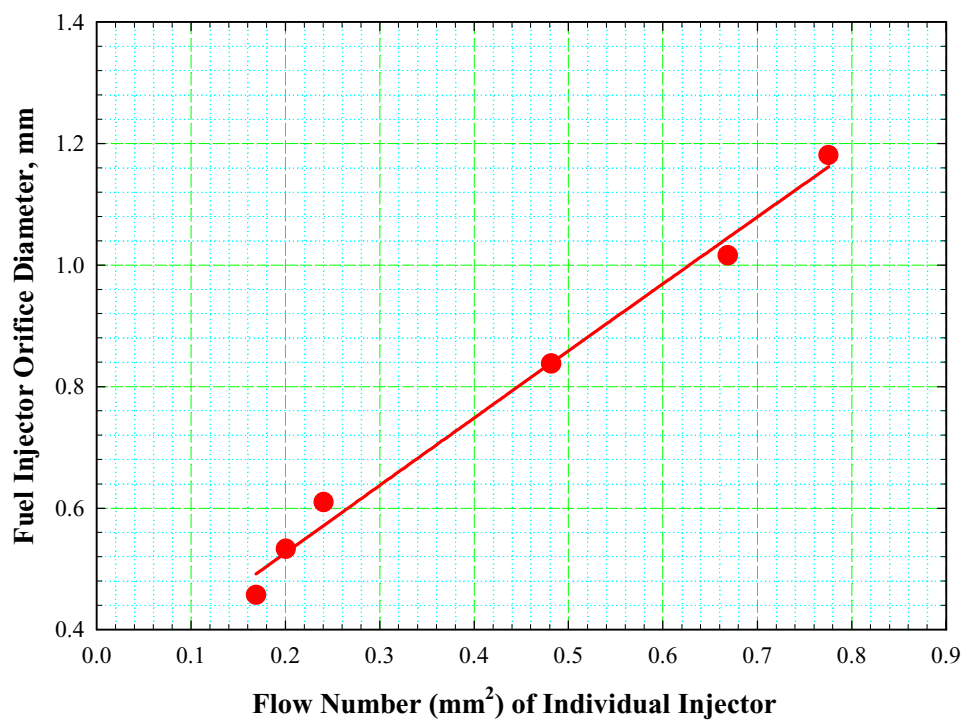


Figure 2. - Flow number as a function of fuel injector orifice diameter

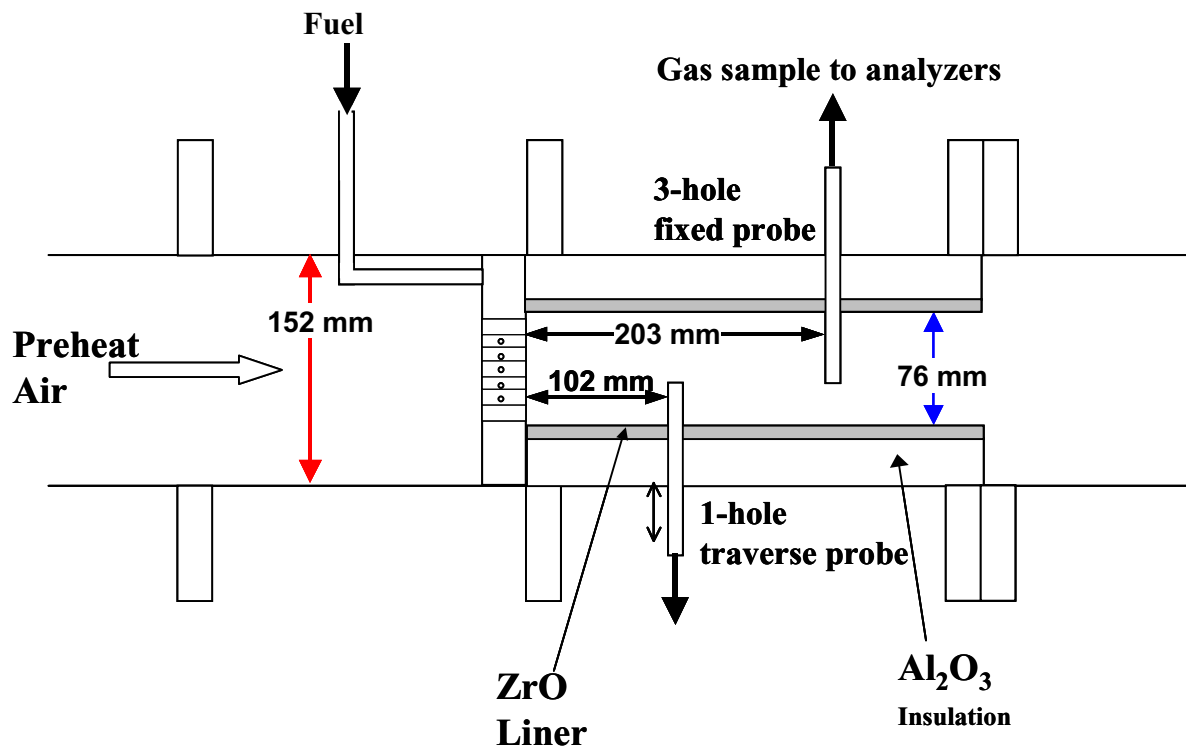


Figure 3. - Test facility schematic

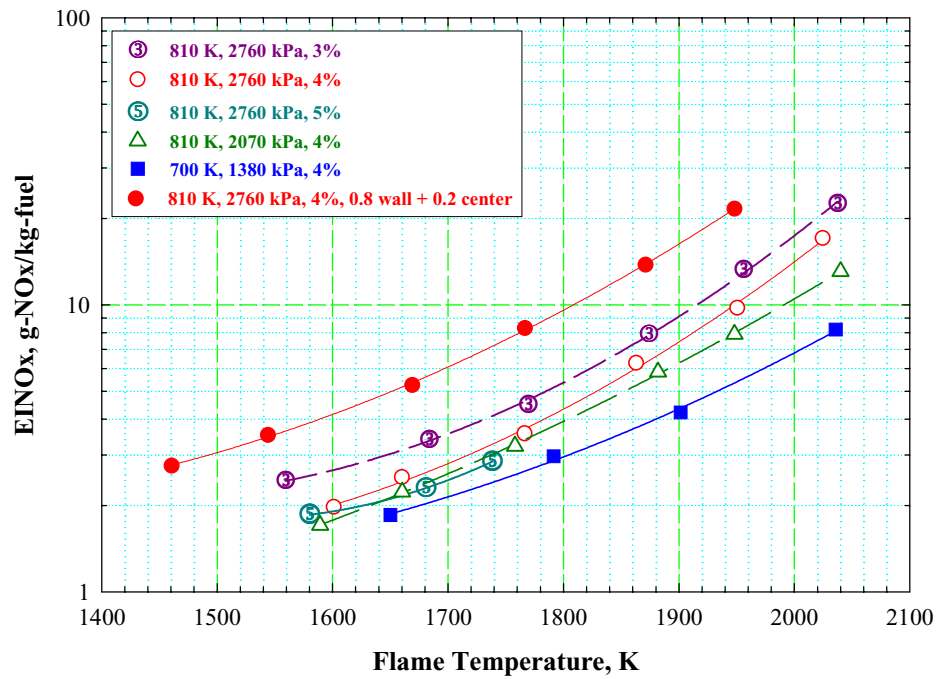


Figure 4a. - Configuration A, 6 injectors @  $FN=0.17 \text{ mm}^2 / \text{injector}$

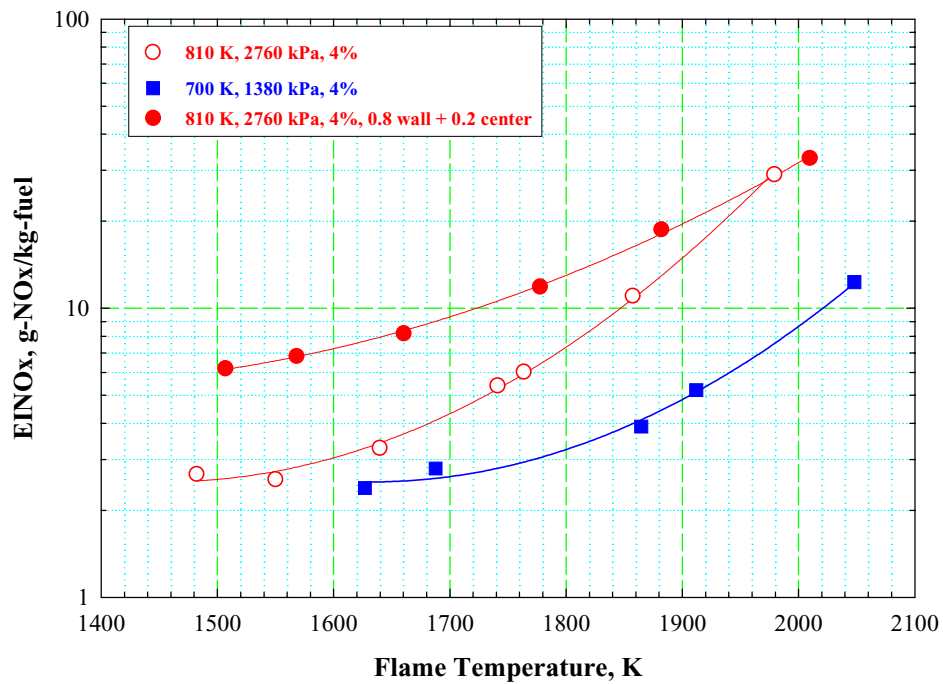


Figure 4b. - Configuration B, 4 injectors @  $FN=0.20 \text{ mm}^2 / \text{injector}$

Figure 4. - NOx emissions index as a function of adiabatic flame temperature for each configuration at various test conditions.

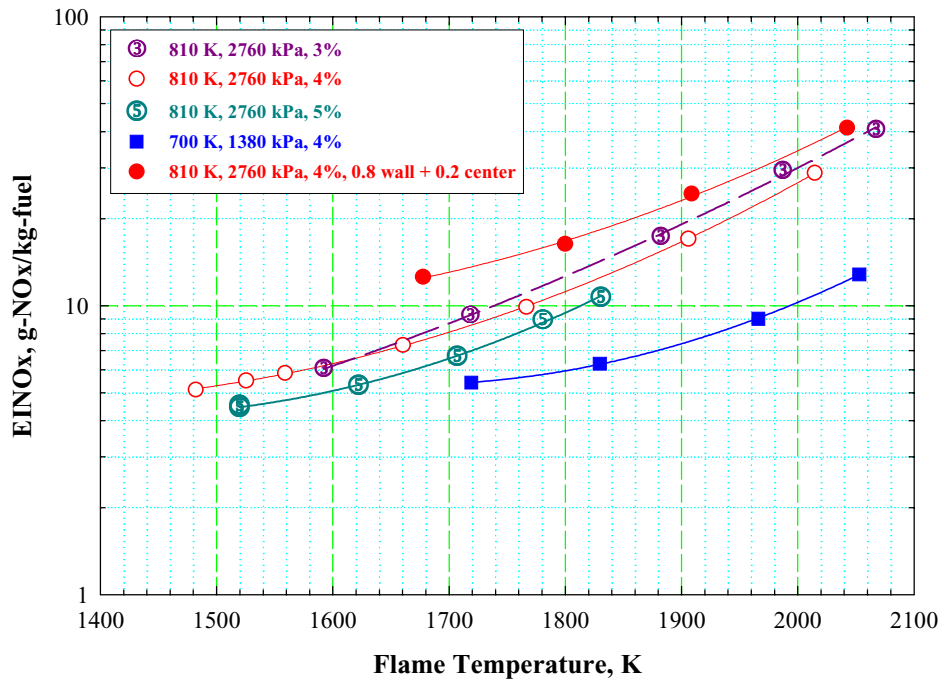


Figure 4c. - Configuration C, 4 injectors @ FN=0.24 mm<sup>2</sup> / injector

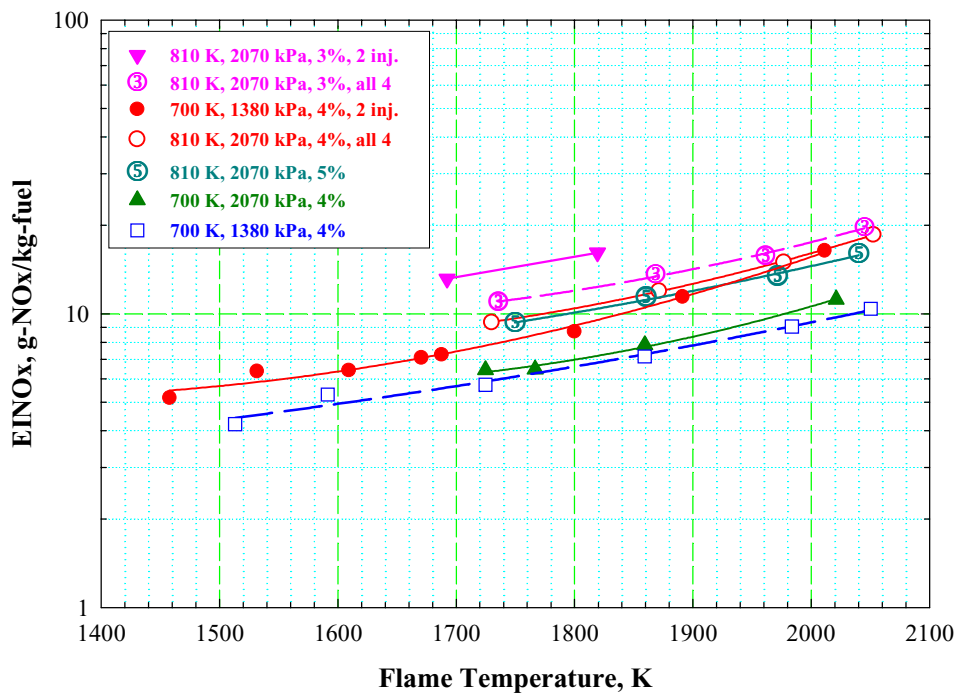


Figure 4d. - Configuration D, 4 injectors @ FN=0.47 mm<sup>2</sup>, fan spray

Figure 4. - NOx emissions index as a function of adiabatic flame temperature for each configuration at various test conditions.

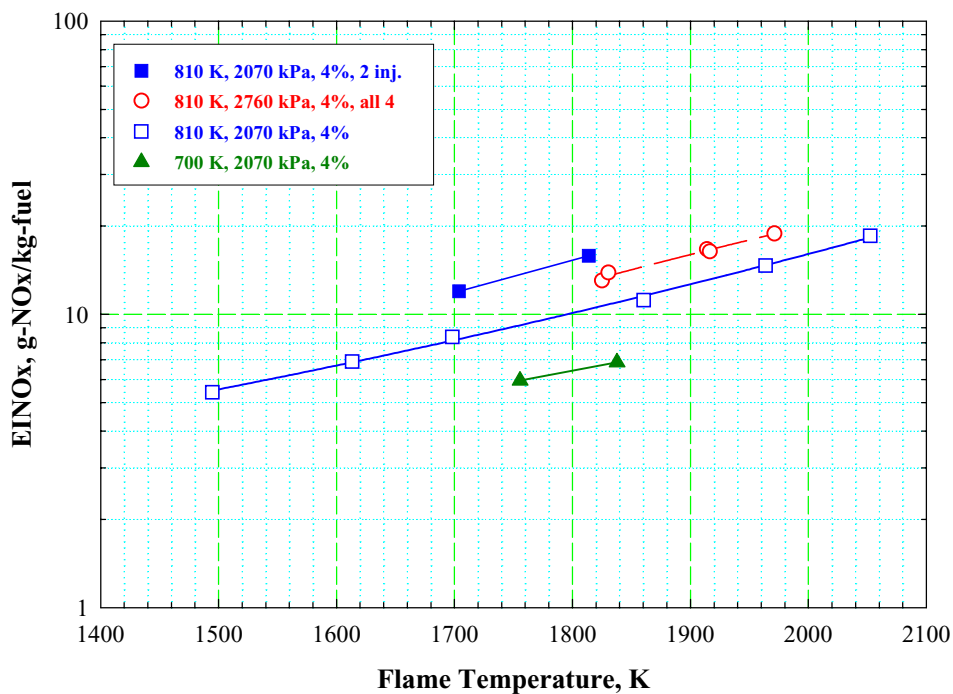


Figure 4e. - Configuration E, 4 injectors @  $FN=0.48 \text{ mm}^2 / \text{injector}$

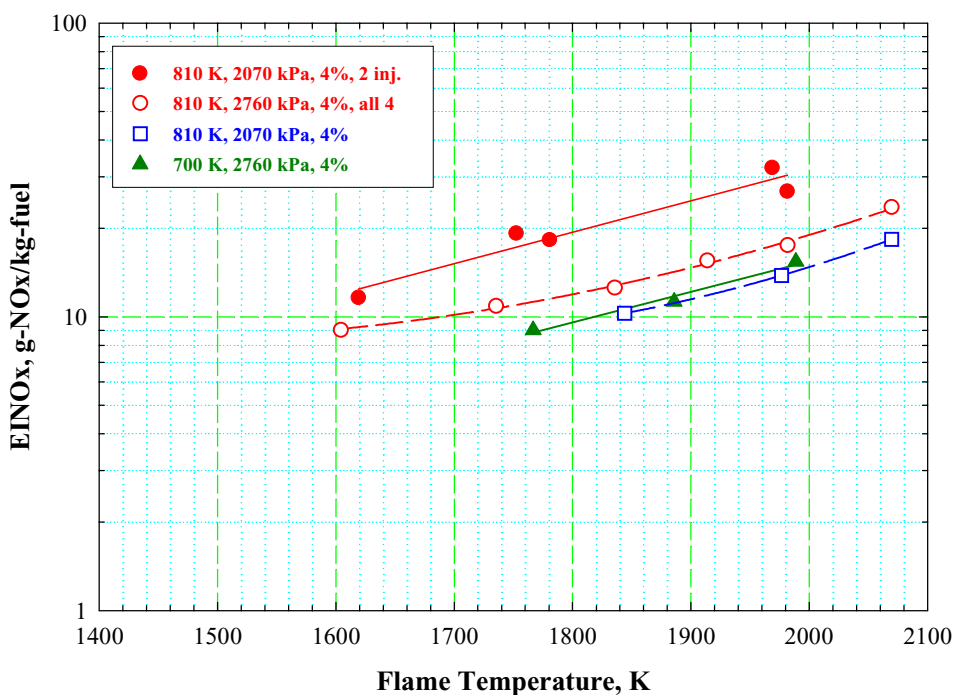


Figure 4f. - Configuration F, 4 injectors @  $FN=0.67 \text{ mm}^2 / \text{injector}$

Figure 4. - NOx emissions index as a function of adiabatic flame temperature for each configuration at various test conditions.

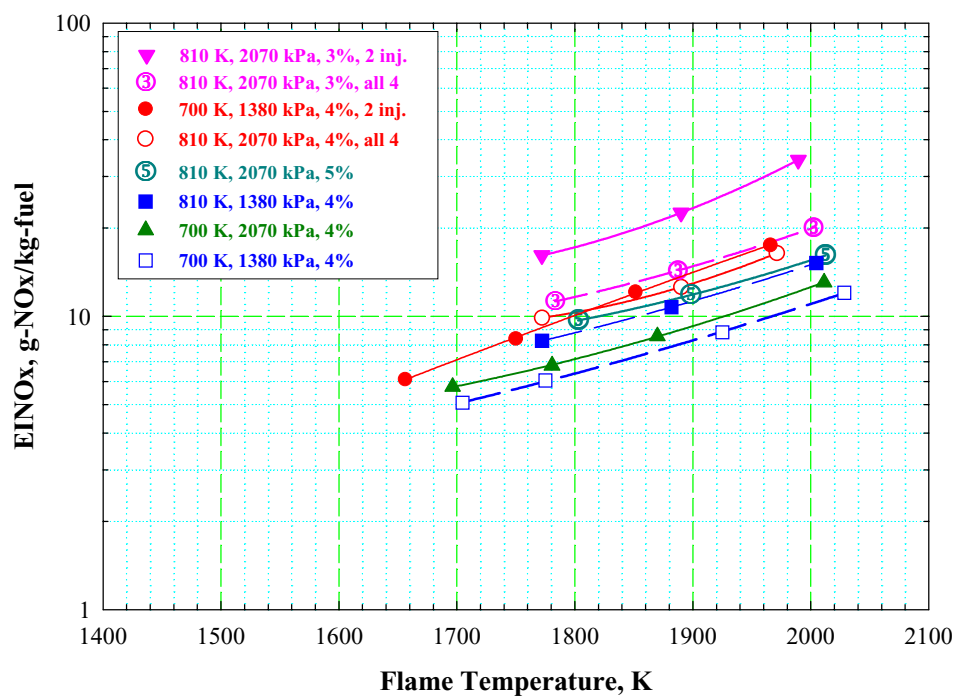


Figure 4g. - Configuration G, 4 injectors @  $FN=0.78 \text{ mm}^2 / \text{injector}$

Figure 4. - NOx emissions index as a function of adiabatic flame temperature for each configuration at various test conditions.



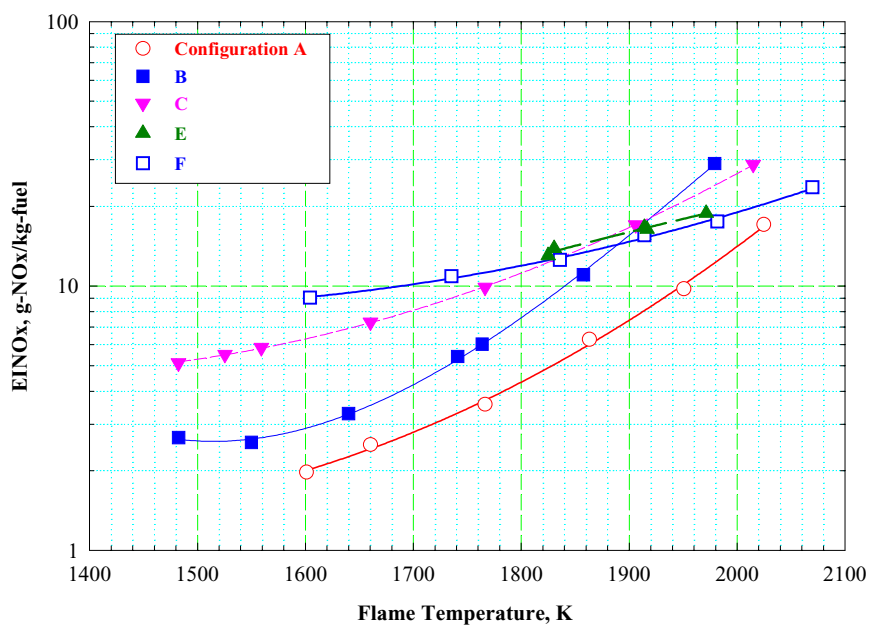


Figure 5a. -  $T_3=810$  K,  $P_3=2760$  kPa,  $\Delta P/P_3=4\%$

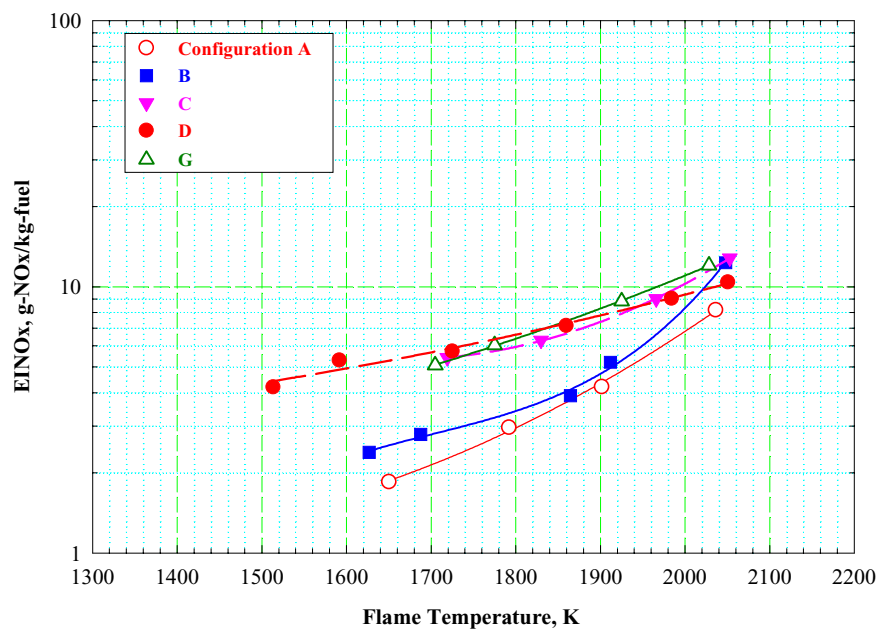


Figure 5b. -  $T_3=700$  K,  $P_3=1380$  kPa,  $\Delta P/P_3=4\%$

Figure 5. - Comparison of NOx emissions with configuration

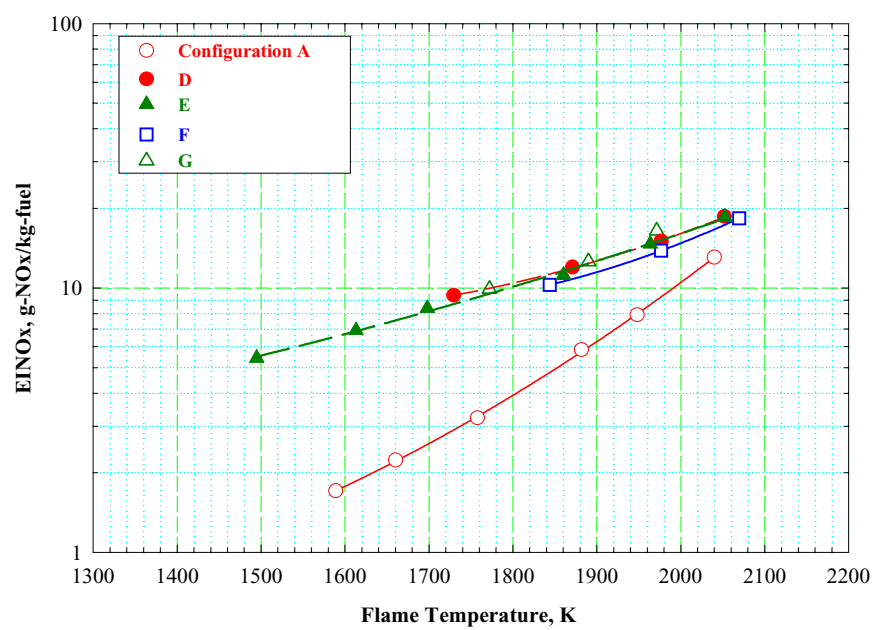


Figure 5c. -  $T_3=810$  K,  $P_3=2070$  kPa,  $\Delta P/P_3=4\%$

Figure 5. - Comparison of NOx emissions with configuration

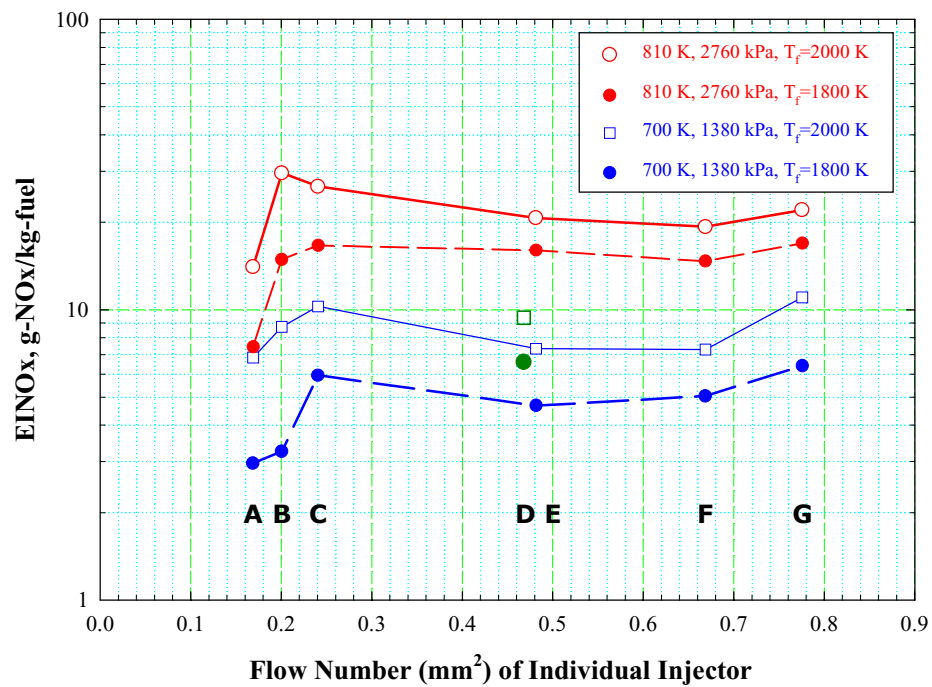


Figure 6. - Comparisons of NOx emissions as a function of fuel injector flow number at  $\Delta P/P_3=4\%$

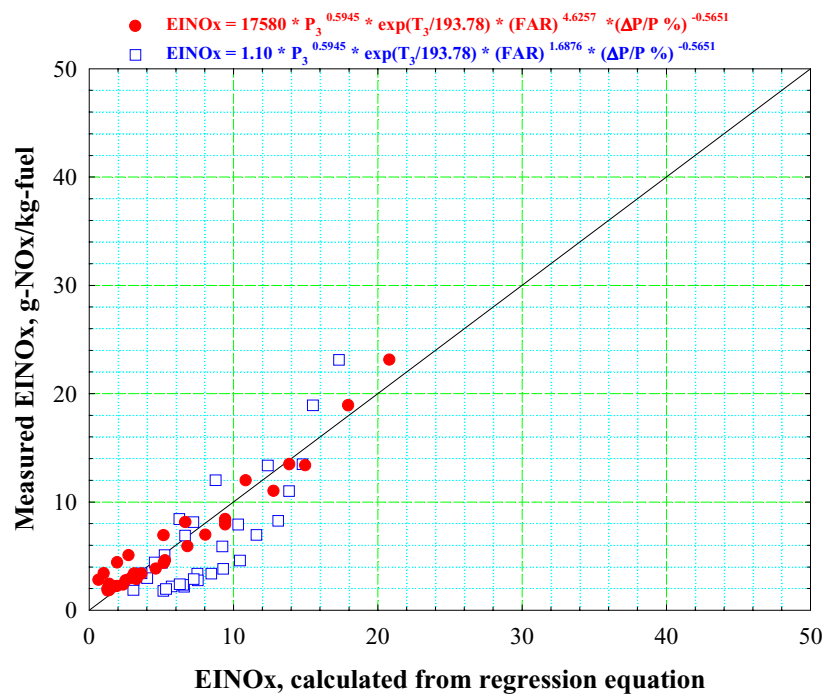


Figure 7a. - Configuration A

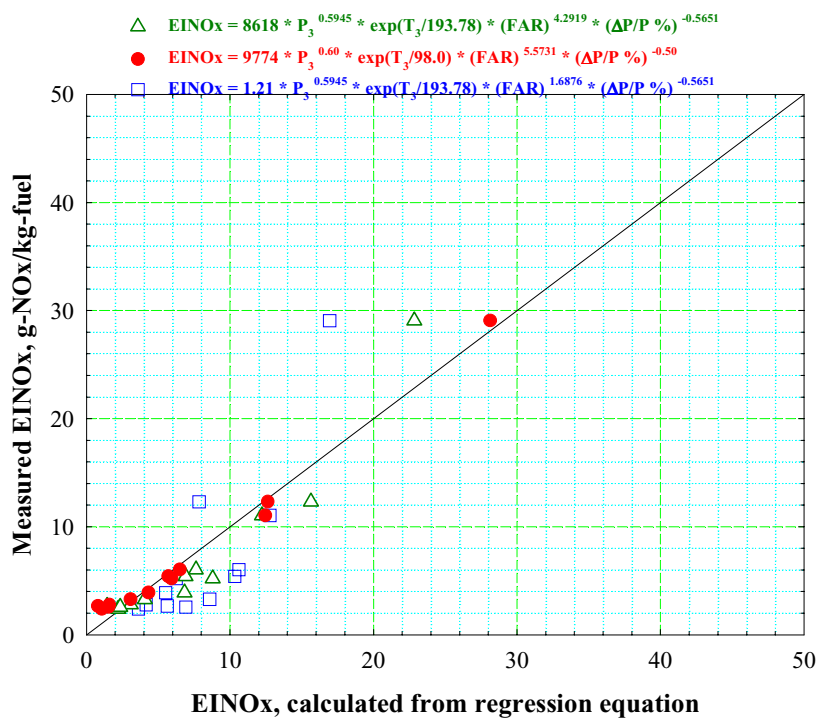


Figure 7b. - Configuration B

Figure 7. - NOx emissions correlated with inlet conditions

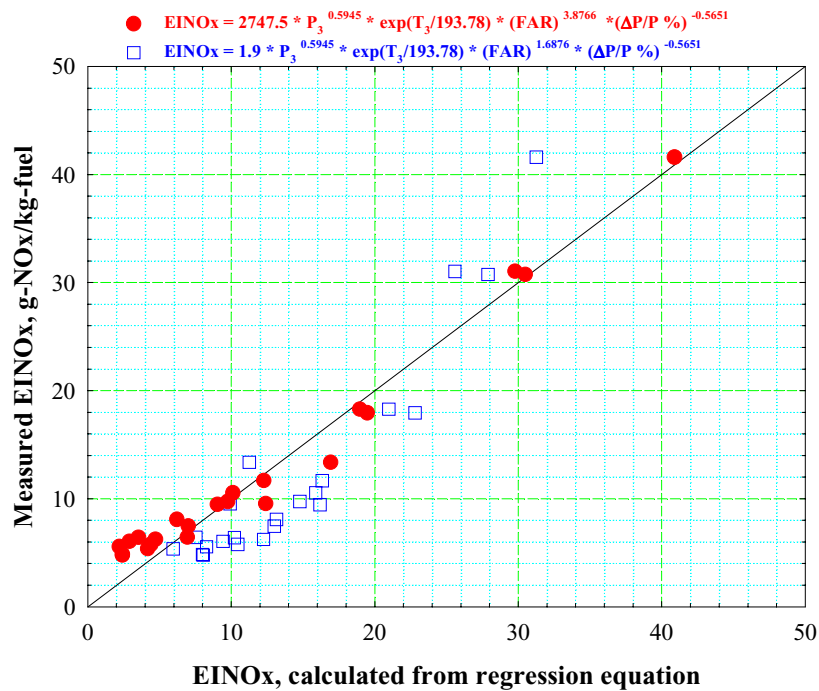


Figure 7c. - Configuration C

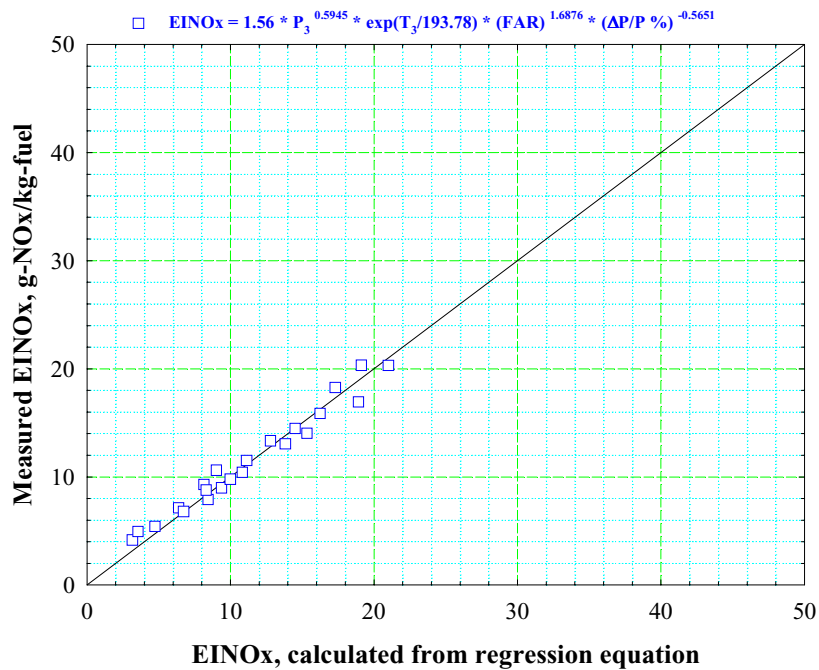


Figure 7d. - Configuration D

Figure 7. - NOx emissions correlated with inlet conditions

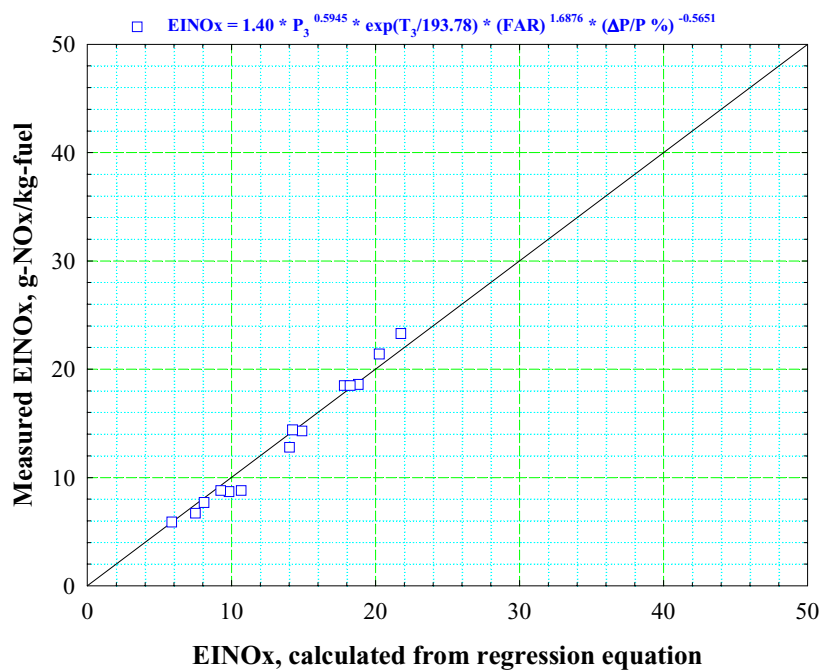


Figure 7e. - Configuration E

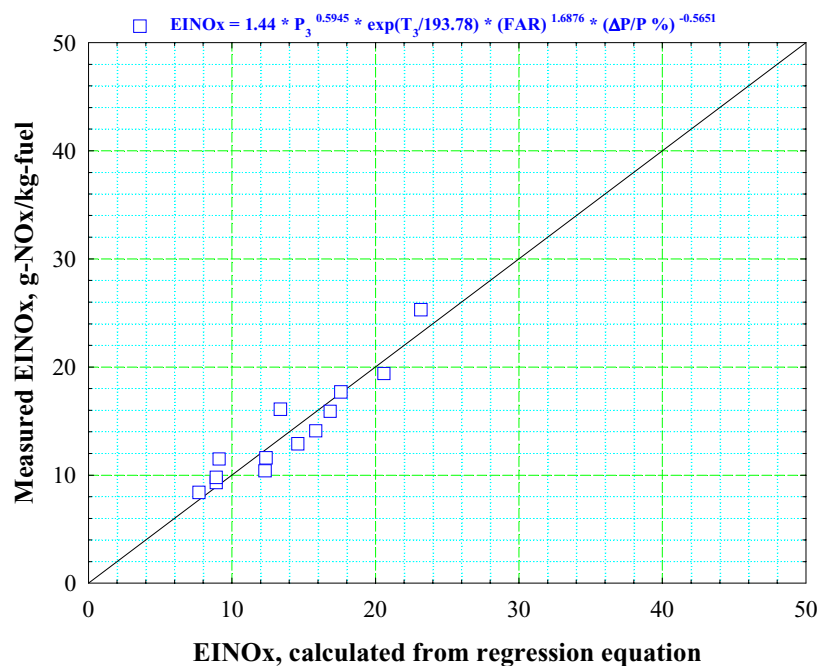


Figure 7f. - Configuration F

Figure 7. - NOx emissions correlated with inlet conditions

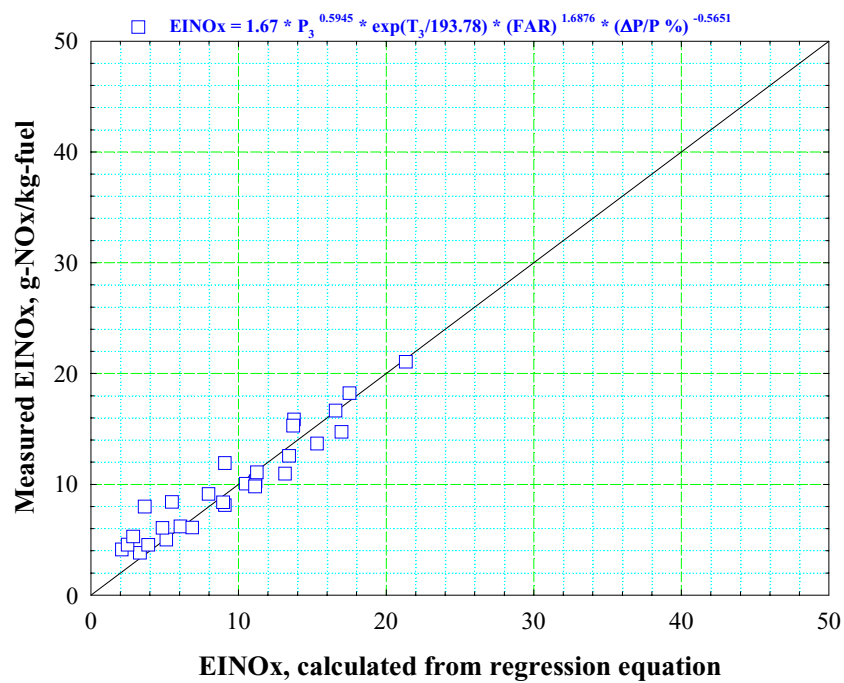


Figure 7g. - Configuration G

Figure 7. - NOx emissions correlated with inlet conditions

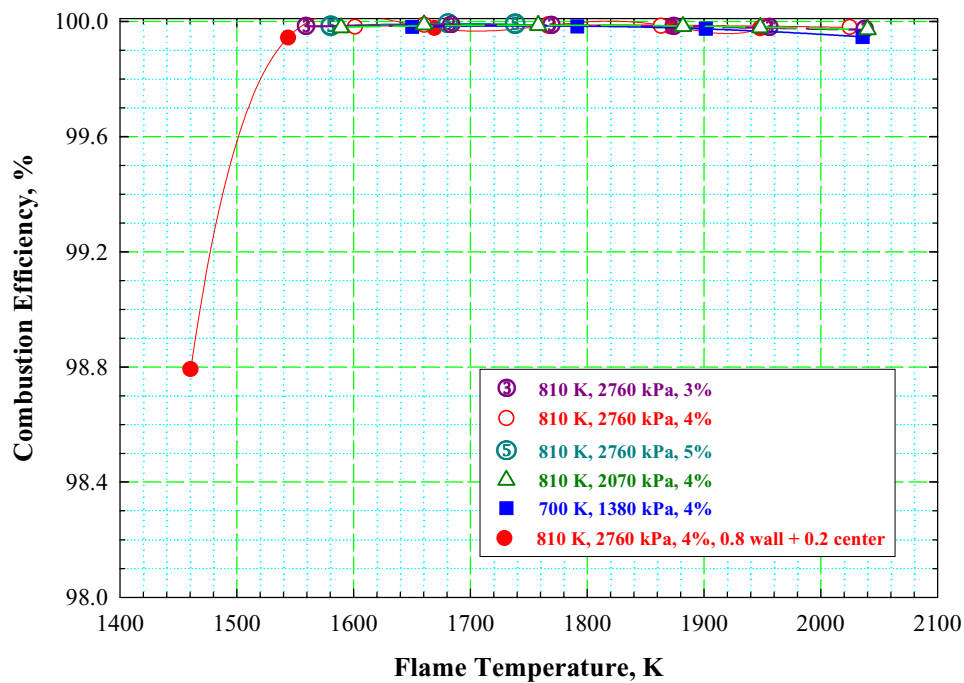


Figure 8a. - Configuration A

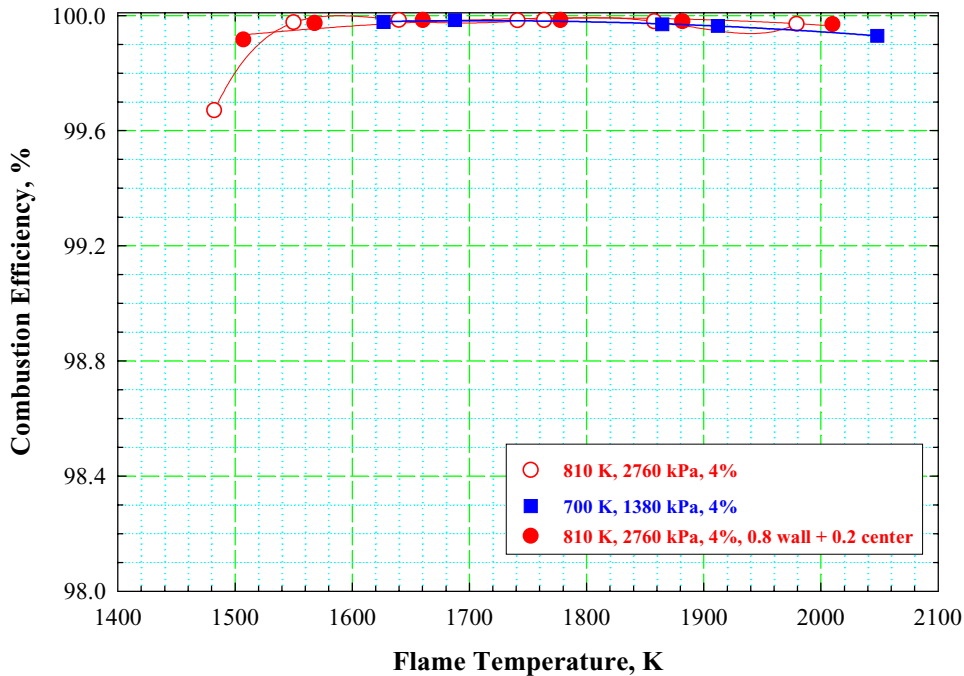


Figure 8b. - Configuration B

Figure 8. - Combustion efficiency as a function of flame temperature for each configuration



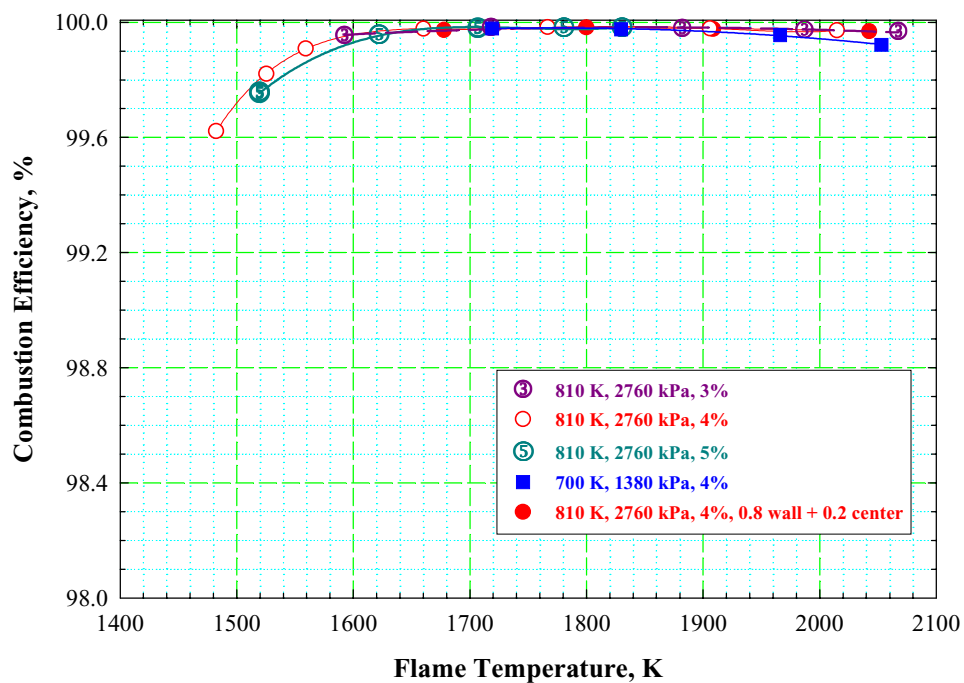


Figure 8c. - Configuration C

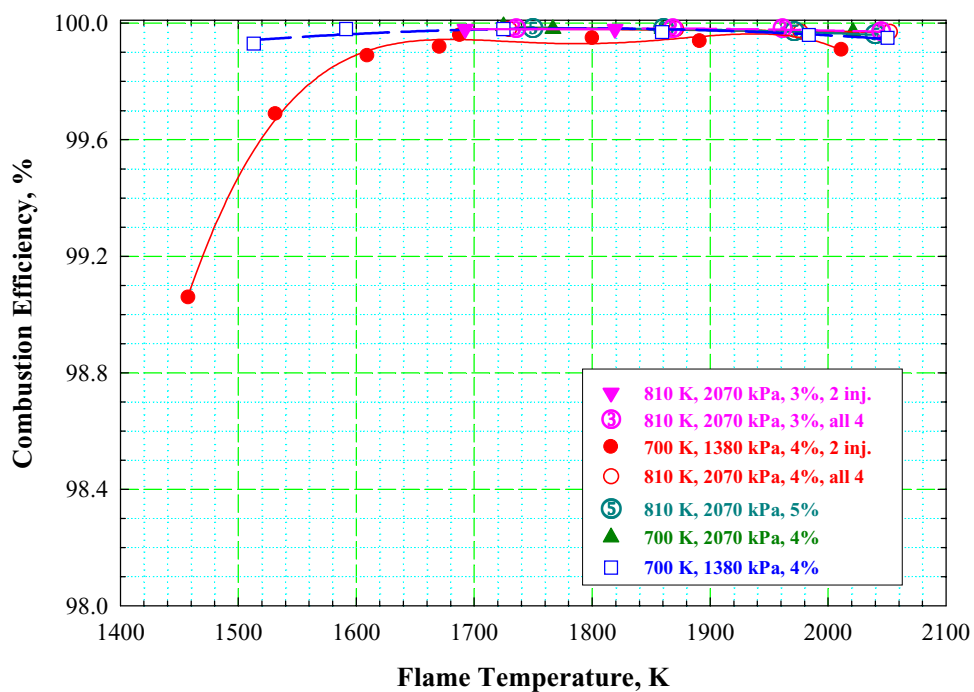


Figure 8d. - Configuration D

Figure 8. - Combustion efficiency as a function of flame temperature for each configuration

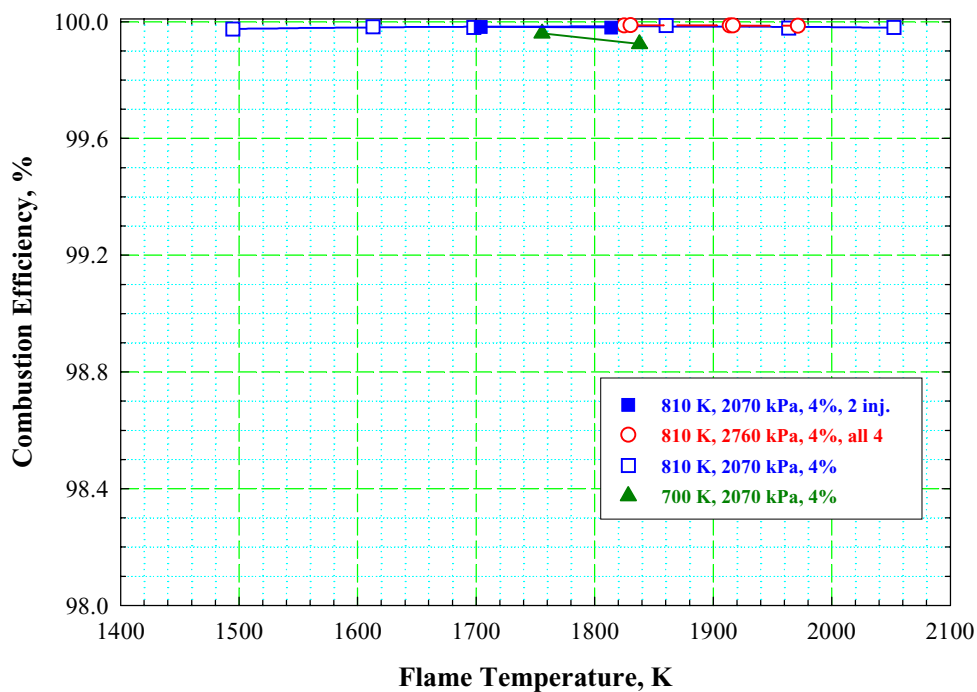


Figure 8e. - Configuration E

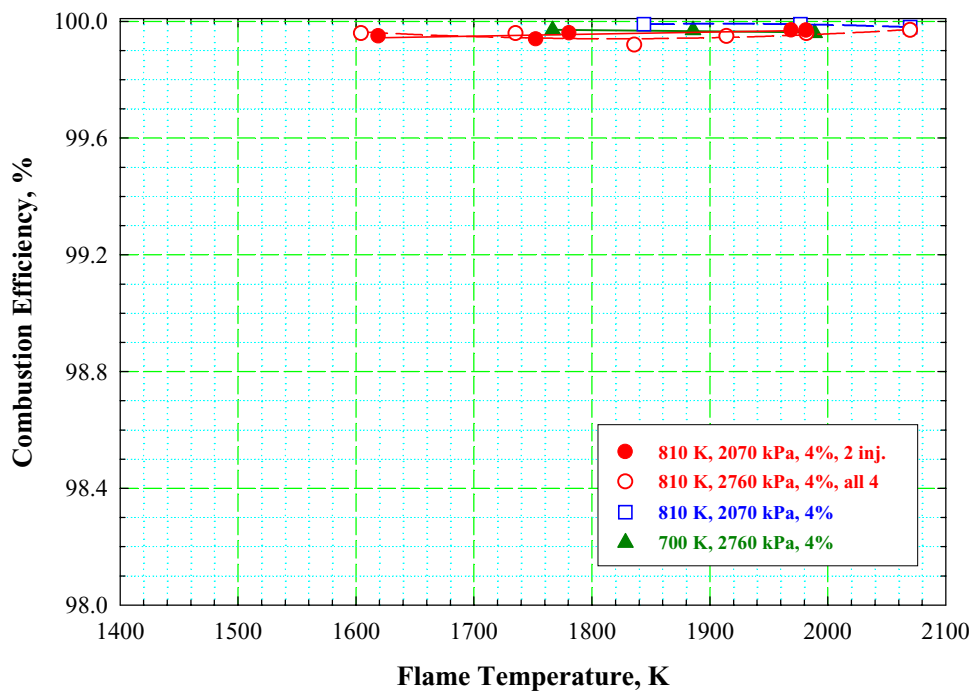


Figure 8f. - Configuration F

Figure 8. - Combustion efficiency as a function of flame temperature for each configuration

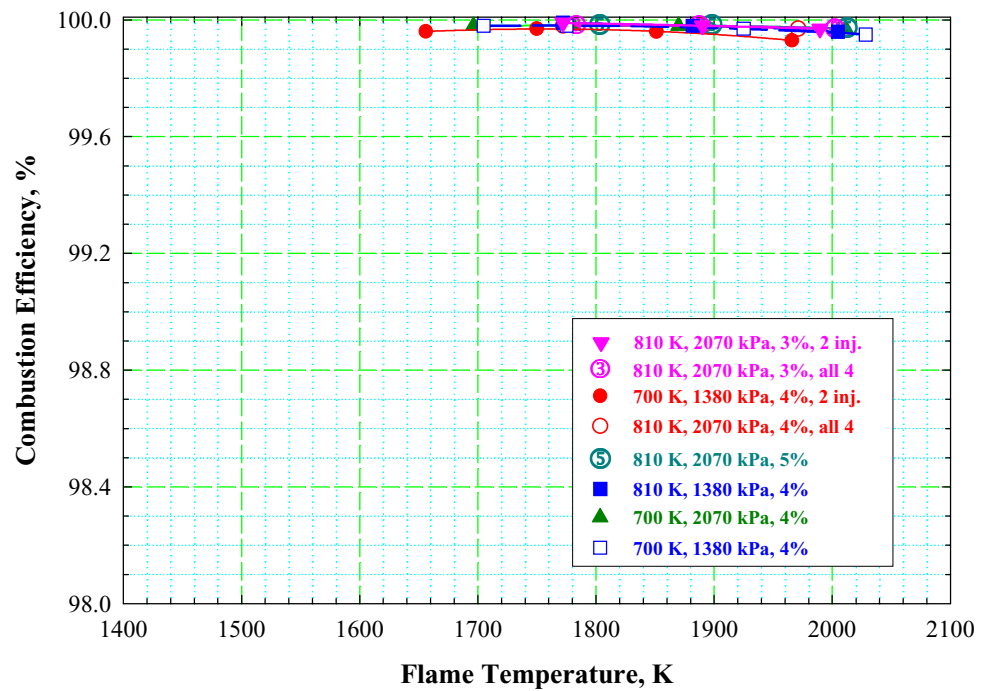


Figure 8g. - Configuration G

Figure 8. - Combustion efficiency as a function of flame temperature for each configuration

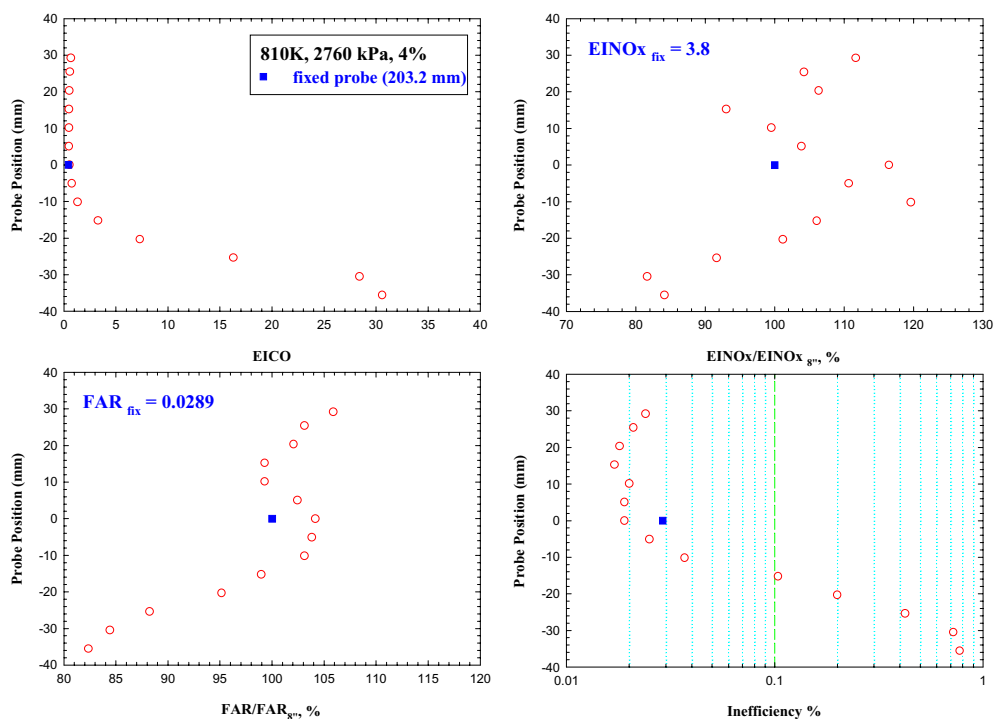


Figure 9a. Configuration A

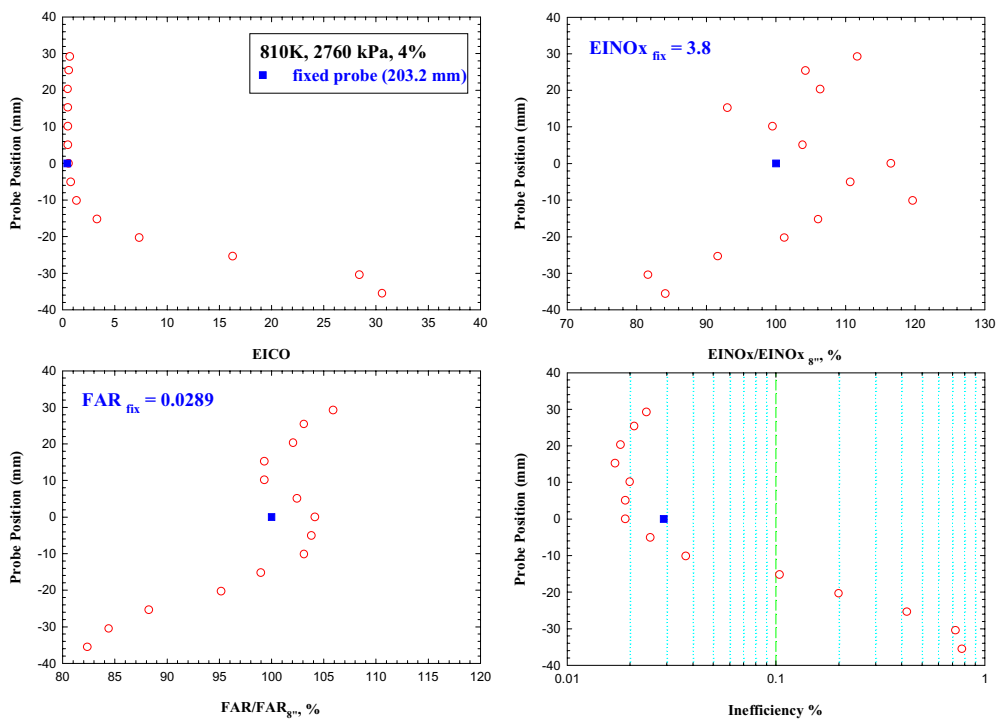
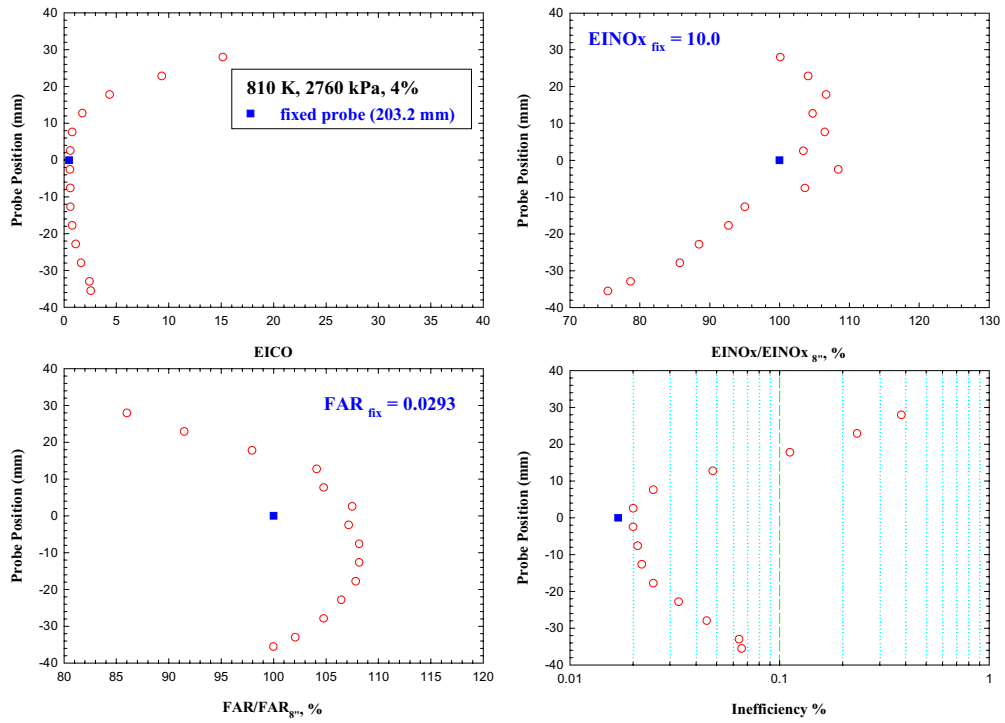


Figure 9b. Configuration B

Figure 9. - Radial profiles of emissions, vertical profile at 102 mm downstream of injector



**Figure 9c. Configuration C**

**Figure 9. - Radial profiles of emissions, vertical profile at 102 mm downstream of injector**

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2001		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE  Flame Tube NOx Emissions Using a Lean-Direct-Wall-Injection Combustor Concept			5. FUNDING NUMBERS  WU-708-28-13-00	
6. AUTHOR(S)  Robert R. Tacina, Changlie Wey, and Kyung J. Choi				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER  E-12950	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA TM-2001-211105 AIAA-2001-3271	
11. SUPPLEMENTARY NOTES  Prepared for the 37th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Salt Lake City, Utah, July 8-11, 2001. Robert R. Tacina, NASA Glenn Research Center; Changlie Wey, QSS Group, Inc., 2000 Aerospace Parkway, Brook Park, Ohio 44142; and Kyung J. Choi, Drexel University, 3141 Chestnut Street, Philadelphia, Pennsylvania 19104-2816. Responsible person, Robert R. Tacina, organization code 5830, 216-433-3588.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Category: 07  Available electronically at <a href="http://gltrs.grc.nasa.gov/GLTRS">http://gltrs.grc.nasa.gov/GLTRS</a> This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  A low-NOx emissions combustor concept has been demonstrated in flame tube tests. A lean-direct injection concept was used where the fuel is injected directly into the flame zone and the overall fuel-air mixture is lean. In this concept the air is swirled upstream of a venturi section and the fuel is injected radially inward into the air stream from the throat section using a plain-orifice injector. Configurations have two-, four-, or six-wall fuel injectors and in some cases fuel is also injected from an axially located simplex pressure atomizer. Various orifice sizes of the plain-orifice injector were evaluated for the effect on NOx. Test conditions were inlet temperatures up to 810K, inlet pressures up to 2760 kPa, and flame temperatures up to 2100K. A correlation is developed relating the NOx emissions to inlet temperature, inlet pressure, fuel-air ratio and pressure drop. Assuming that 15 percent of the combustion air would be used for liner cooling and using an advanced engine cycle, for the best configuration, the NOx emissions using the correlation is estimated to be <75 percent of the 1996 ICAO standard.				
14. SUBJECT TERMS  Gas turbine combustor emissions; NOx emissions; Lean-direct injection			15. NUMBER OF PAGES 31	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	